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POWER-CONDITIONING REQUIREMENTS FOR ION ROCKETS

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POWER-CONDITIONING REQUIREMENTS

FOR ION ROCKETS

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SUMMARY

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Data are presented that are important in the design of electrically propelled spacecraft. An explanation is given for what has been done with regard to the power-conditioning equipment for small ion rockets up to 3 kw including the problems encountered. The expected power distribution of 30-kw electron-bombardment and contact-ionization rockets is presented, although engines of this size have not been tested. The electrical power requirements are presented in a form compatible with system studies.

Author

INTRODUCTION

Electric propulsion is in a state of early development. Some basic research is still being carried out in this area, but effort is beginning toward development of complete systems. The system developer needs to know the particular problems associated with integrating ion thrustors into a propulsion system. This paper attempts to spell out some of the problems that have occurred in previous system developments and some of the factors to be considered in larger systems.

Papers published previously by Brewer and Work[1] have described a small ion rocket system that is presently being developed by the Hughes Research Laboratory for NASA. Childs and Cybulski[2] have described the present and future flight plans of NASA for which ion rockets are being developed, although some of the dates have been modified since publication.

The first part of this paper deals with the system development for ballistic testing of two different types of ion rockets. The power-conditioning requirements, problems involved with power conditioning, and the corrective action are discussed. Also, the small amount of development work on slightly larger systems that has been started is presented.

Finally, the electrical requirements of a single 30-kw ion rocket are discussed. Ion rockets of this size have not been tested, but this discussion serves to point out the particular problems expected when power-conditioning equipment is scaled to larger sizes. The power distribution and the types of loads are presented as well as the required regulation. No attempt has been made to prove that these requirements are optimized with respect to system considerations.

SERT 1

Payload

Space Electric Rocket Test (SERT) is an NASA program to test ion rockets in ballistic flights. The first flight is scheduled for the third quarter of 1964. A four-stage Scout vehicle will be used to launch a 350-lb payload containing two ion rockets. Fifty minutes of engine operation will be obtained above 200 n miles. During this time, each of the thrustors will be operated separately, and engine performance data will be telemetered to a ground receiving station.

The payload package will be spin stabilized at about 100 rpm. The two thrustors are mounted to produce opposite torques about the spin axis. The thrust can be computed from the change in spin speed over the length of the test. A sketch of the payload capsule is shown in Fig. 1.

Thrustors

One of the thrustors to be tested in the SERT 1 flight was developed at the NASA Lewis Research Center.[3] The power conditioning for this thrustor was developed under NASA contract by the TRW Electromechanical Division. This thrustor employs electron bombardment of mercury vapor to produce ions. The other thrustor is being developed at the Hughes Research Laboratory under NASA contract.[1] The power conditioning for this thrustor was developed under NASA contract by Hughes Aircraft Company, Culver City, California. The Hughes thrustor employs contact ionization of cesium vapor passing through hot, porous tungsten.

The principal thrustor characteristics and operating conditions are listed in Table I.

Power Conditioning - Contact-Ionization Thrustor

A schematic diagram of the Hughes cesium contact ion thrustor and its associated power conditioning is shown in Fig. 2. The power requirements for this thrustor are listed in Table II. Only the decelerator electrode is at ground or spacecraft potential, while the accelerator is at a negative potential and the rest of the thrustor is elevated at the ionizer potential.

To convert the payload battery power to the various a-c and d-c potentials with the electrical

[1]G. R. Brewer and G. A. Work, "An Ion Engine System for Flight Testing," AIEE CP 62-1162, June 1962.

[2]J. H. Childs and R. J. Cybulski, "Flight Tests and Early Missions for Electric Propulsion System," ARS Paper 2653-62.

[3]H. R. Kaufman, "An Ion Rocket with an Electron-Bombardment Ion Source," NASA TN D-585, January, 1961.

isolation required, the design approach (see Fig. 3A) employs two 2-kc square-wave bridge inverters each common to several individually regulated outputs. Payload space limitation made it necessary to house the power conditioning in four separate boxes as shown. Voltage regulation of each supply is accomplished by pulse-width modulation of the 2-kc square wave with a magnetic amplifier in the primary of the output transformer. Fig. 3B shows a typical block diagram. The pulse-width-modulated a.c. is transformed to desired voltage levels for a-c loads but rectified and filtered for d-c loads.

Each bridge inverter is powered by a square-wave driver. The inverter driver stage, incorporating overload trip and automatic reset provisions, is switched by a saturable core 2-kc square-wave oscillator. Overloads sensed in each bridge by a current transformer clamp the corresponding inverter driver. After a 2-sec delay, the inverter driver is recycled automatically.

The design allows each inverter to handle approximately one-half the normal load. An overload in the ionizer potential shuts down the number 1 inverter that closes the feed valve to prevent excess propellant from accumulating in the accelerator region. An excess of propellant would cause arcing when the full ionizer potential was applied; in fact, it was necessary to control the rate of rise of the ionizer potential (soft turn-on) to allow clean out of the thrustor electrodes after an arcing overload shutdown. If the overload condition has cleared, the feed valve is energized after a delay of a few seconds.

The magnetic amplifier pulse width modulators employ a differential amplifier for set and reset control; so, essentially, all the control is done at ground potential. Current and voltage transformers provide the feedback signal isolation necessary for most supplies.

The resistance changes of the heaters are large (as much as 1:10) during the warmup cycle. It was necessary to employ a current limit control in the ionizer heater regulator to limit inverter current until the operating temperature range is reached. The temperature regulation is accomplished by sensing both load voltage and current and by regulating to an established load resistance.

All voltage and current measurements are converted to a 0- to 5-v signal for telemetry.

The power supplies were thoroughly bench tested with static loads and knife switches to simulate overloads. Many failures were encountered later when Hughes integrated the supplies with a thrustor. An ion thrustor proved to be basically a difficult load for a semiconductor power supply. Initially, the Hughes design employed a single inverter common to all supplies, but after a siege of inverter transistor failures, it was realized that the thrustor overload transient power requirements exceeded the transistor capabilities. Thus, a two-inverter configuration was employed.

In the bridge inverter a problem was encountered as a result of the turn-off time of the transistors being greater than their turn-on time, creating a short circuit during switching. It was necessary to employ circuitry to delay the turn on of the drive for a few microseconds.

Under certain conditions, ion thrustors can draw exceedingly high electrode currents. It was necessary to incorporate rapid shutdown to improve inverter reliability.

A second type of overload that proved difficult to handle is caused by high voltage arcing between the ion thrustor electrodes. Destructive voltage transients created by engine arcing were coupled through the interwinding capacitance of the output transformers into the inverter and control electronics. Shunting capacitance and zener diodes provide some protection from these voltage transients; also electrostatic shielding in the transformer proved effective in reducing the transients.

High voltage transformer and filter design for pulse-width-modulated square-wave excitation proved quite an art. It was necessary to employ π-wound distributed section secondaries to minimize layer voltage stress and leakage inductance. The combination of leakage inductances, the effective distributed capacitance in high-voltage transformers (due to a large turns ratio and a large number of secondary turns) and the square-wave excitation caused ringing and overshooting. A π-filter was necessary because it looked more resistive under most load conditions, thus providing damping to reduce the overshoot. Then it was necessary to incorporate a bleeder of 10 percent to load the filter under no-load conditions.

The reactance of the transformer required commutating diodes across each of the inverter transistors for protection. Capacitance with resistive damping was used to tune out the inductive effect.

More integration problems were encountered when attempts were made to operate the supplies in a vacuum. Careful attention to potting techniques were necessary. No exposed high voltage terminals were allowed because of corona and breakdown (Paschen's Law), which occurred due to outgassing of the supply during evacuation. Teflon insulated wire had to be etched so that plotting would adhere. Insulation in the connectors had to be fabricated from Teflon instead of the commonly used silicon rubber types as corona leakage would occur due to localized pressure in the connector.

Power Conditioning - Electron-Bombardment Thrustor

A schematic diagram of the Lewis mercury-electron-bombardment ion thrustor circuit and its associated power conditioning is shown in Fig. 4. The individual power requirements for this thrustor are listed in Table III. Some of the required power is furnished directly from isolated batteries.

Basically, the TRW design approach (see Fig. 5A) differs from Hughes in that it employs a number of smaller inverters instead of two larger ones. It should be pointed out, however, that their power output of 1.4 kw is greater than the Hughes supply of 750 w. Each high-voltage supply (see Fig. 5B) employs two inverters (one being pulse width modulated for regulation) with the secondaries of their output transformers' connected in series adding. The pulse width modulated inverter is operated in a current limit mode.

The ionization chamber potential supply is unregulated, but the accelerator supply employs a series regulator in the 56-v supply for voltage regulation.

The other supplies each employ a single-pulse-width-modulated inverter and operate in a current limit mode. Overloads are sensed by d-c current transducers in the two high voltage supplies, and shutdown is accomplished by removing the 28-v d.c. to the two drivers. This removes all power except the boiler heater supply. Reset is automatic after 4 sec. The response for shutdown is 12 msec for accelerator overloads and 6 msec for the ionizer chamber overloads.

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All supplies are recycled full-on with the exception of the cathode heater where one-half power for 4 sec was necessary during warmup.

All control signals, except for the boiler heater control, are referenced to ground potential. The boiler temperature is regulated by a thermistor sensing element.

Space limitations allow two packages, and they are divided as shown in Fig. 5A. All currents and voltage measurements are converted for 0- to 5-v d-c signals for telemetry.

Originally, the TRW contractural effort was limited to packaging a power supply designed and breadboarded by NASA Marshall Space Flight Center, Huntsville, Alabama, but tested for only 1/2 hour with a well-behaved thrustor. The arcing problem diminishes with time as thrustors clean up under vacuum operation. After packaging, integration was attempted with a flight model ion thrustor and problems were encountered. As a result, the TRW contract was changed to a design and development effort.

The final design incorporated zener diodes across all inverter transistors and electrostatic shielding in the transformers. The boxes were pressurized to eliminate the high-voltage-corona effects during operation in vacuum tanks with the mercury plasma.

An electronic shutdown of the supply under transient arcing conditions proved too fast for proper operation of the Lewis thrustor. A certain amount of energy in the arc will sometimes clean up the source of the original discharge and prevent a recurrence. A relay operated overload shutdown proved effective for the Lewis thrustor.

TRW found that mercury vapor tubes could be used effectively to simulate engine arcing for bench testing. These tubes give a satisfactory overload characteristic with a large amount of success. TRW employed simulation techniques with power tubes in the development of a satisfactory supply.

DEVELOPMENT OF LARGER ION ROCKET SYSTEMS

Thrustors

Larger thrustors (up to 30 kw) are being developed for ground testing to study the effects of scaling and interactions between adjacent thrustors. One thrustor is being developed by the Hughes Aircraft Company under NASA contract NAS 3-4109. The thrustor is a strip-beam unit that has the performance goals listed in Table IV.

A second 3-kw thrustor is being developed by the Electro-Optical Systems, Inc. under NASA contract NAS 3-2516. The performance goals are listed in Table IV. This thrustor is an electron-bombardment type that employs a self-heating or autocathode.

Power Conditioning

At the present time, no development work has been done to provide power conditioning for the EOS 3-kw thrustor. The power conditioning for the Hughes 3-kw thrustor is being developed by the Hughes Aircraft Company under NASA contract NAS 3-3565. The estimated power requirements for this thrustor are listed in Table V.

The design approach shown in Fig. 6 required two Hughes SERT I style bridge inverters for handling the power for the ionizer potential supply, which is unregulated and is obtained by series adding the outputs of a pair of bridge rectifiers that are excited by the separate inverters and output transformers. The supply is capable of being turned on in steps of one-half or full-on and employs overload protection by clamping the inverter drive.

The accelerator supply employs a single bridge inverter, a transformer, and a rectifier and is regulated in a way that the total accelerating potential (ionizer-accelerator) is held constant. Series regulation is accomplished by a 2-kc switching regulator for pulse width modulation of the 56-v primary power. An L-C filter provides smooth d.c. to the inverter.

ELECTRIC PROPULSION MISSIONS

A possible early mission for electric propulsion is attitude control and station-keeping of synchronous, stable, platform satellites. Thrustor system development for such a mission is being carried out under NASA contract NAS 3-2510. Ground testing of this system is proceeding to demonstrate feasibility and long life under pulsed operation in a simulated space environment. The power-conditioning-system capacity (1100-w peak) will allow simultaneous station-keeping and attitude control about three axes. The power requirements for this system are listed in Table VI. Since the engines are operated in a low duty cycle, the bulk of the engine power is handled by two Hughes SERT I inverters, which are switched on by command from the control system when engine thrust is required.

In order to conserve weight, the design employs silicon controlled rectifiers (SCR) for switching the a-c loads. Switching is accomplished in the secondary of the transformer, which is elevated to the ionizer potential, so a single transformer can be common to several engines. Hence, the most critical design areas were the SCR - a-c switching. Since the SCR's are referenced to the 1.5-kv ionizer potential, the SCR's heat sinks, firing transformers, and gate-firing networks were incorporated into potted modules. This was essential in order to have close control over the high-voltage-insulation integrity. These modules are controlled directly from the power control logic at ground potential. On command, the desired switching path for the a-c power supplies to the appropriate engine load is completed.

A one-axis system is presently being evaluated at the Lewis Research Center, after having been developed and built by the Hughes Research Laboratories. The one-axis system consists of a pod containing three thrustors, controls, a propellant system, and a power supply. Each pod will contain two strip-beam 2.2×10^{-3} newton thrustors for attitude control and an annular-beam 6.7×10^{-3} newton thrustor for station-keeping.

Initiation and termination of thrust will be accomplished by the opening and closing of a valve in the propellant feed line to each thrustor. If close tolerance thrust levels prove to be desirable, voltages to the accelerator electrodes can be controlled.

There are also scientific missions that can be performed by a 3-kw solar-powered electric satellite, which are presented in detail in reference 4. These missions include the spatial survey of the intensities of the energetic particles trapped in the earth's magnetic field and a world magnetic survey.

In the power ranges above 3 kw, simple mission analysis calculations indicate the great dependency of electrically propelled spacecraft performance on electric power sources. Specific power, the ratio of power output to weight, is extremely important. The greater the specific power of the power source, the greater the payload capabilities of the spacecraft, or the greater the spacecraft acceleration, the shorter is its flight time for a given mission. With maximum specific power as a goal, system analysis is needed to determine the optimum electrical conversion equipment required between the prime power source and the electric thrustors. Some work relating to the preceding optimization is being done by the Westinghouse Electric Corporation under NASA Contract NAS 5-1234.

Electric propulsion systems for the power levels above 3 kw are expected to utilize clusters of ion thrustors. The size of these thrustors would be determined by the state of the art, performance, system weight, and reliability. System analysis, including the parameters of the nuclear power source, the power-conditioning equipment, and the electrical propulsion devices, is needed to arrive at a minimum system weight. Power conditioning for these high power systems will require extensive effort in component development for the high temperature and nuclear radiation environment.

SOME PROBLEMS IN POWER CONDITIONING

One of the critical components to be considered in the power conversion system is the power switching devices. Due to the inherent characteristic of the ion thrustor to arc between the high voltage electrodes, the capability of limiting the power in the arc is essential. If the arc should continue, because of the capabilities of the power source, the electrode structures would probably be destroyed, and the thrustor would fail. In the normal mode of engine operation, a delay of several seconds and a soft turn-on could clean up the electrodes and allow the engine to continue thrusting.

There are several NASA contracts to extend the state-of-the-art technology of power conversion components. Contract NAS 3-2546 with the General Electric Company is to develop technology and fabricate electrical switchgear, contactors, and circuit breakers, suitable for use in space nuclear electrical systems. The General Electric Company is Also developing high temperature ceramic rectifiers, thyratrons, and voltage regulator tubes for long-term use in space nuclear electric power systems under NASA Contract NAS 3-2548. These contracts are directed by the Space Power Systems Division at the Lewis Research Center.

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Because of the importance of the breakdown and arcing phenomena in ion thrustors, an experimental program was undertaken at the Lewis Research Center to identify the breakdown and arcing phenomena in an electron-bombardment ion thrustor. Stover[5] presents the nature and general features of these phenomena. He suggests the possibility that breakdown is caused by a high field resulting from the collection of positive ions on a thin nonconducting contaminant film on that electrode. It would seem obvious that instability and self-extinction of low-current arcs should occur following breakdown, with low-inductance circuits. Self-extinction was observed, but often the arc persisted. Stover postulates that films of contaminants on the electrode systems also caused sustained arcing. Perhaps improved prelaunch and postlaunch techniques of thrustor conditioning can lead to a minimum amount of sustained arcing, but this problem cannot be overlooked in the design of power-conditioning circuitry.

POWER CONDITIONING FOR 30-kw THRUSTORS

The maximum size of a thrustor is limited by three factors: (1) The ion optics of the accelerator system, (2) the material consideration because of high operating temperatures, and (3) fabrication limitation due to critical dimensions. A reasonable assumption, based on present and expected improved technology might be a 30-kw thrustor. This size will be subject to change as development of thrustors progresses and the mission requirements become known, but it should not vary too drastically. When considerably more power is to be used for propulsion, the larger thrustors will be obtained by using clusters of the 30-kw unit, and the power distribution will be in the same proportions as is presented here.

Fig. 7 illustrates the power distribution that might be expected in a 30-kw electron-bombardment ion thrustor as a function of the specific impulse (high propellant exhaust velocity). The specific impulse is equal to the thrust divided by the propellant mass flow rate or by the equation $I_{SP} = 123\ \eta_f\sqrt{\varphi_{net}}$, where φ_{net} is the ionization chamber potential and η_f is the propellant

[4]R. N. Olson and R. A. Boucher, "Need Electric Propulsion Wait for the Development of Nuclear Power Sources" AIAA Paper 63035.

[5]J. B. Stover, "Electric Breakdown and Arcing in Experimental Ion Thrustor Systems," AIAA Paper 63057-63.

utilization. The thrustor that these curves represent is slightly different from the Lewis electron-bombardment thrustor previously discussed, as it uses cesium as the propellant and employs an arcing autocathode in the ionization chamber. The ion beam current and voltage for both this electron-bombardment thrustor and a contact-ionization thrustor are presented in Fig. 8 as a function of the specific impulse. As the specific impulse increases, both the beam power and the ionization chamber potential increase, but the beam current decreases.

Most of the power in a thrustor goes into the ion beam where it is converted into thrust. The potential of the ionization chamber is always in the d-c kilovolt range to provide the desired high specific impulse. The propellant utilization used in determining the curves for the electron-bombardment thrustor is 90 percent. The regulation of the ionization chamber potential could be about 5 percent for a 0.80 to full-load operating range, because it would affect the thrust. Ripple would also be permissible at about 5 percent level even though it would mean a slight decrease in thrust. The impedance of this load would be almost entirely resistive, but the current would be determined by the amount of ionization in the ionization chamber.

The accelerator voltage would be the other high voltage supply in the thrustor. It is estimated that the current will be about 1 percent of the beam current, except during high voltage arcing. The accelerator supply, operating under normal conditions, would need a limited amount of power, but it must be protected from transients. The load would be very slightly capacitive, but its current would be determined primarily by the ion beam current. Again, it would be desirable to have a maximum of 5 percent ripple and 5 percent voltage regulation between 0.80 to full-load conditions. The voltage of the accelerator is d.c. and is assumed equal in magnitude to the ionization chamber potential, but the polarity is negative.

The arc-ionization power supply might be the most critical supply in this thrustor system. Floating at the ionization potential, the arc potential is assumed to be 6 v d.c., but the current was assumed to be 110 times the beam current. The supply should be current regulated to 1 or 2 percent in the 0.80 to full-load range, and ripple should be minimized, since thrust is directly related to arc current. The load would be that of a low voltage arc.

The neutralizer heater power was assumed to be 20 w/emitted amp, the neutralizer being a wire filament on the downstream side of the accelerator electrodes, thermally emitting an electron current equal to the beam current. This supply should be current regulated, although it could be about 10 percent in the 0.80 to full-load range, and it could be a.c. or d.c. The load would be entirely resistive, but it might change as much as tenfold from cold to emitting temperature. This supply would be at ground potential.

The electron-bombardment thrustor also needs a magnetic field supply. This supply would see an inductive load, although the coil windings are spread out thus minimizing the inductive effect. Permanent magnets, to generate the magnetic field, have not been used in this analysis because long-term clustering effects have not been evaluated, although thrustors with permanent magnets have been operated.

The propellant system supply was assumed to be 100 w full load, either a.c. or d.c. This supply would be at the ionization chamber potential. The propellant supply would provide heat for the propellant storage tanks and the propellant feed lines. These temperatures would be required to be maintained within a few degrees of a preselected level.

It is very probable that all the above mentioned supplies will need to be controlled by low level signals near ground potential. The controls will provide on-off operation, solenoid valve control, and perhaps voltage and current regulation.

The contact-ionization-thrustor power distribution is shown in Fig. 9. In this figure, the ion beam power is equal to the beam current times the net potential of the beam φ_n. The principal assumptions made in calculating these power curves are that (1) the propellant utilization η_f is 96 percent, (2) the propellant is cesium, and (3) the power radiated by the ionizer is 870 w/beam amp. This third assumption is from actual thrustor operating data of smaller units and represents the major power loss in the thrustor.

The potential to the ionizer is a positive d-c voltage, which determines the operating specific impulse. The current is the beam current and is found in Fig. 8 as a function of the specific impulse. It would be permissible to have a regulation of 5 percent within the 0.80 to full-load limits and a ripple of 5 percent. The load would be entirely resistive, but the current is determined by the propellant feed rate and the ionization efficiency.

The most critical power supply would be the ionizer heater supply. Since the operating temperature is about 1500° K and power is lost by radiation in proportion to the fourth power of the temperature, any temperature higher than optimum will result in serious power losses. If the temperature falls below a minimum critical temperature, the ionization process is stopped and the thrustor fails to operate. Although the power supply is floating at the ionizer potential, the power can be either a.c. or d.c. The load would be resistive, but the resistance changes 10 to 1 or more from startup to operating temperature.

The accelerator potential is a negative d-c voltage assumed equal in magnitude to the ionizer potential. The accelerator impingement current was again assumed to be 1 percent of the ion beam current. Because an attempt is made to shield the ionizer from heat losses, the ion optics for the accelerator are critical, and the accelerator voltage should have 5 percent regulation in the 0.80 to full-load range, but ripple should be limited to 1 percent. The load impedance would be only slightly capacitive.

The neutralizer and propellant-feed-system supplies have the same characteristics as those described for the neutralizer and propellant supplies in the electron-bombardment thrustor. The important factor to emphasize is that the propellant supply is at the ionizer potential. This system would also have the same control requirements as those in the electron-bombardment ion thrustor.

CONCLUDING REMARKS

Electric thrustors have proved to be a difficult load for solid state electronics. There are several peculiar characteristics involving both the environment and the thrustor operating mode that have caused problems. Through careful design and thorough integration procedures, these problems can be overcome.

The reality of an electric propelled spacecraft is still in the distant future. Because of the importance of specific power on mission success, every effort should be extended to lower the specific weight. An area of prime concern is in the conversion of the primary voltages into voltage suitable for electric thrustors. Technology programs are now being directed into this area, but more reliable and higher temperature operating components are needed.

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TABLE I. - THRUSTOR PERFORMANCE CHARACTERISTICS

OF SERT I THRUSTORS

	Lewis Thrustor	Hughes Thrustor
Ion beam outside diameter, m	0.1	0.08
Overall thrustor diameter, m	0.19	0.1
Thrustor mass (including mount), kg	4.2	6.4
Propellant	Mercury	Cesium
Specific impulse, sec	5000	9000
Total input power, w	1400	750
Power efficiency, percent	50	38
Propellant-utilization efficiency, percent	80	96
Thrustor, newtons	28.5×10^{-3}	7.1×10^{-3}
Beam current, amps	0.280	0.058
Current density, amps/n^2	69	35
Beam perveance, micropervs	2.24	0.15

TABLE II. - SERT I HUGHES ION THRUSTOR POWER REQUIREMENTS

Supply	Voltage	Current	Remarks
V_1, Ionizer potential	+5000 v_{dc}	60 ma	(1) 5 percent regulation (3) Soft turn-on (2) 5 percent ripple (4) Overload shutdown
V_2, Accelerator	-2000 v_{dc}	2 ma	(1) 5 percent regulation (3) 30-ma overload capacity (2) 5 percent ripple (4) Overload shutdown
V_3, Neutralizer bias	100 v_{dc}	100 ma	(1) 5 percent regulation (2) 5 percent ripple
V_4, Neutralizer heater	11.5 v_{ac}	5.5 amp	(1) 5 percent temperature regulation based on E-I characteristics of heater
V_5, Boiler heater	32 v_{ac}	2.0 amp	(1) 5 percent temperature by E-I characteristics of heater (2) Floats at +5000 v_{dc}
V_6, Ionizer heater	32 v_{ac}	11.0 amp	(1) 5 percent temperature by E-I characteristics of heater (2) Floats at +5000 v_{dc}
V_7, Feed valve	8 v_{dc}	200 ma	(1) Floats at +5000 v_{dc} (2) Regulation ±10 percent

TABLE III. - SERT I LEWIS ION THRUSTOR POWER REQUIREMENTS

Supply	Voltage	Current	Remarks
V_1, Neutralizer heater	10 v_{dc}	20 amp	(1) Power provided by isolated silver-zinc primary battery
V_2, Boiler heater	30 v_{ac}	3 amp	(1) Thermistor control (3) Floats at 2500 v_{dc} (2) Only supply that remains on during shutdown
V_3, Cathode Heater	10 v_{ac}	20 amp	(1) 2 percent regulation (3) Floats at 2500 v_{dc} (2) One-half power for 4 sec during warmup
V_4, Anode	50 v_{dc}	5 amp	(1) 5 percent regulation (3) 70 to 80 V_{dc} for arc ignition (2) 5 percent ripple (4) Floats at 2500 v_{dc}
V_5, Ionization chamber potential	+2500 v_{dc}	310 ma	(1) 5 percent ripple (3) Overload shutdown (2) Current limiting (4) Unregulated voltage
V_6, Accelerator	-2000 v_{dc}	10 ma	(1) 5 percent regulation (3) Current limiting (2) 5 percent ripple (4) Overload shutdown
V_7, Magnet	10 v_{dc}	18 amp	(1) Power provided by isolated silver-zinc primary battery

TABLE IV. - 3-kw-THRUSTOR PERFORMANCE CHARACTERISTICS

	Hughes thrustor	EOS thrustor
Overall frontal dimensions, m	0.10 by 0.13	0.17 diam.
Engine mass, kg	5.5	2.3
Propellant	Cesium	Cesium
Specific impulse, sec	6000	6900
Total input power, kw	2.17	2.22
Power efficiency, percent	75	82.5
Propellant-utilization efficiency, percent	98.0	91.5
Thrust, newtons	5.3×10^{-2}	5.0×10^{-2}
Beam current, amps	0.685	0.489
Current density, amps/m^2	150	78
Beam perveance, micropervs	5.68	1.78

TABLE V. - HUGHES 3-kw ION THRUSTOR POWER REQUIREMENTS (ESTIMATED)

Supply	Voltage	Current	Remarks
V_1, Ionizer potential	+2400 v_{dc}	650 ma	(1) Unregulated (2) Overload shutdown
V_2, Accelerator	-5300 v_{dc}	60 ma	(1) 5 percent regulation to keep sum $V_1 + V_2$ constant (2) Overload shutdown
V_3, Neutralizer bias	100 v_{dc}	650 ma	(1) 5 percent regulation
V_4, Neutralizer heater	25 v_{ac}	5 amp	(1) 5 percent temperature regulation
V_5, Boiler heater	25 v_{ac}	2 amp	(1) 5 percent temperature regulation (2) Floats at 2400 v_{dc}
V_6, Ionizer heater	35 vac	20 amp	(1) 5 percent temperature regulation (2) Floats at 2400 v_{dc}
V_7, Feed valve	25 v_{dc}	1 amp	(1) ±10 percent regulation (2) Floats at 2400 v_{dc}

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TABLE VI. - HUGHES ION THRUSTOR POWER REQUIREMENTS FOR 3-AXIS

ATTITUDE-CONTROL AND STATION-KEEPING SYSTEMS

Supply	Voltage	Current	Remarks
Ionizer potential	+1500 v_{dc}	200 ma	
Accelerator	-4000 v_{dc}	63 ma	
Neutralizer heater	10 v_{ac}	6 amp	
Feed valve	10 v_{ac}	800 ma	
Ionizer heater (attitude)	15 v_{ac}	5 amp	(1) 120-w peak during warmup
Ionizer heater (station keeping)	45 v_{ac}	5 amp	(1) 350-w peak during warmup
Boiler	25 v_{ac}	200 ma	

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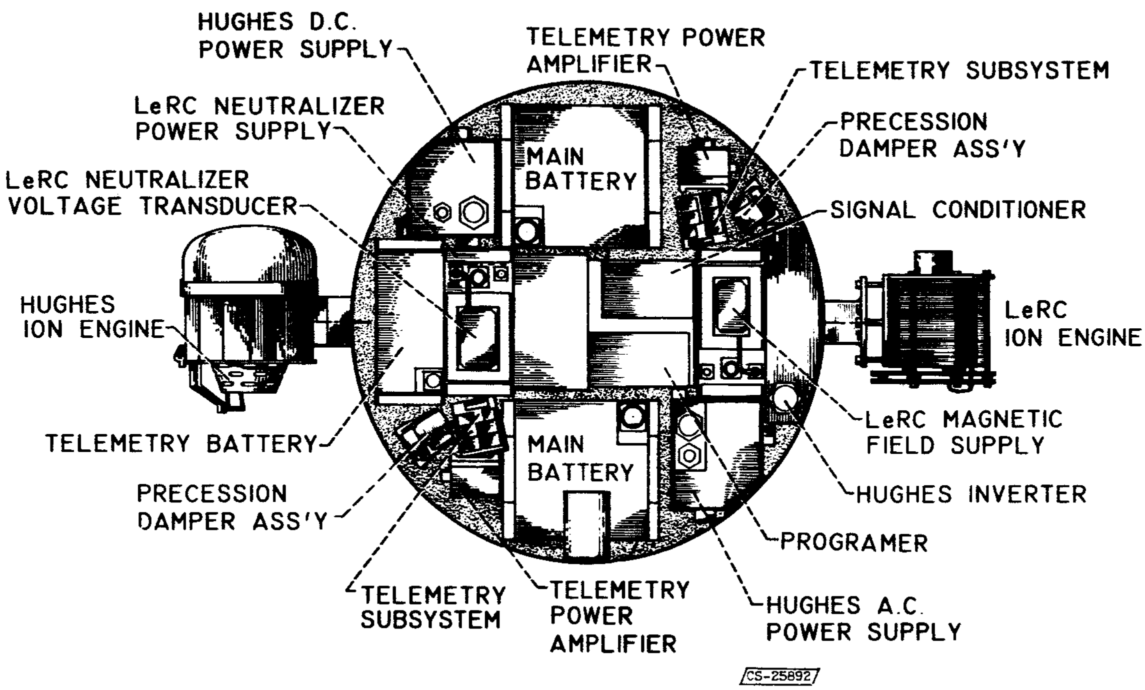

Fig. 1. - SERT I payload capsule.

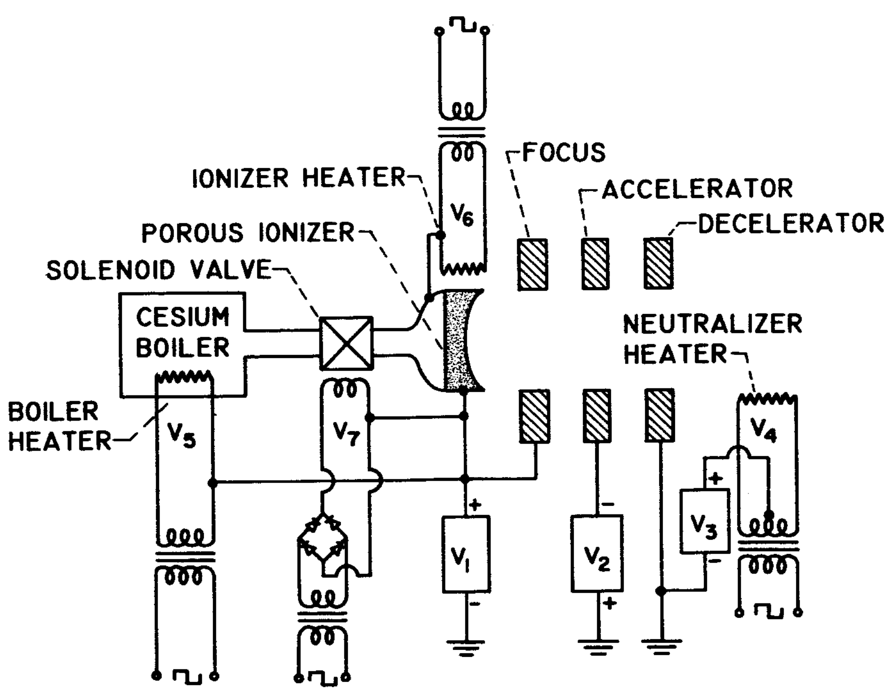

Fig. 2. - Schematic diagram of Hughes ion thrustor.

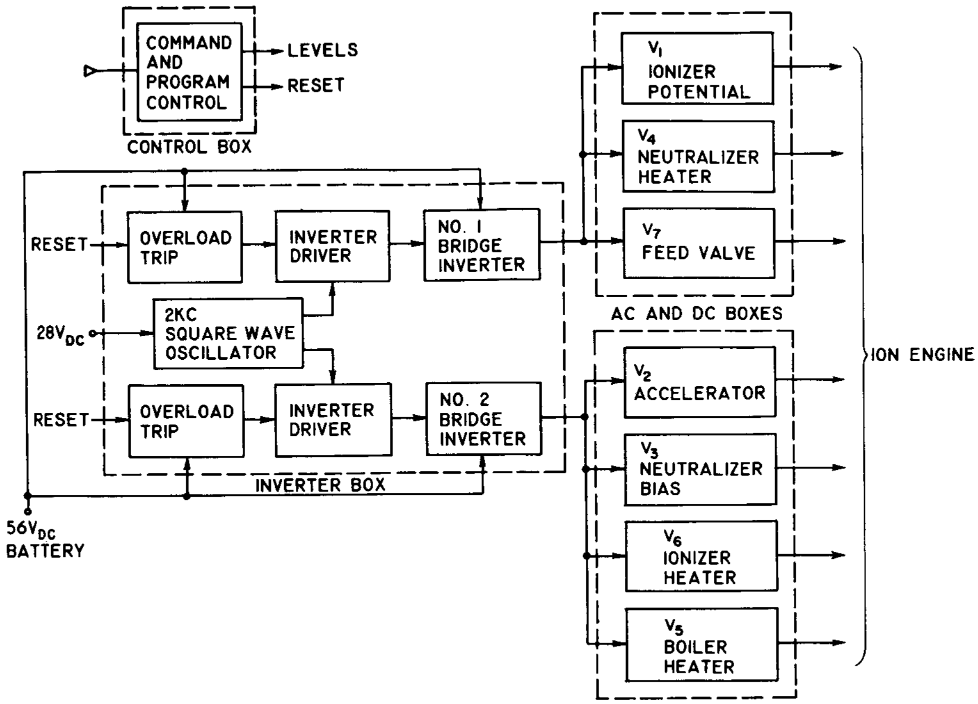

Fig. 3a. - Schematic diagram of Sert I Hughes ion thrustor power system.

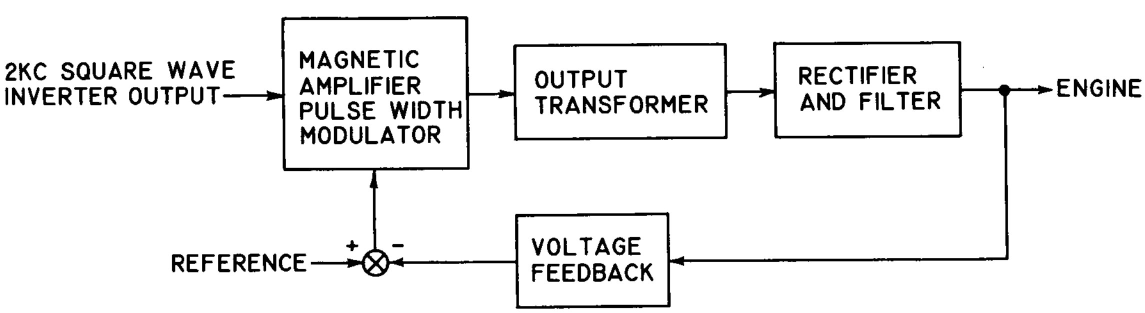

Fig. 3b. - Concluded. Typical regulator for Hughes ion thrustor supply.

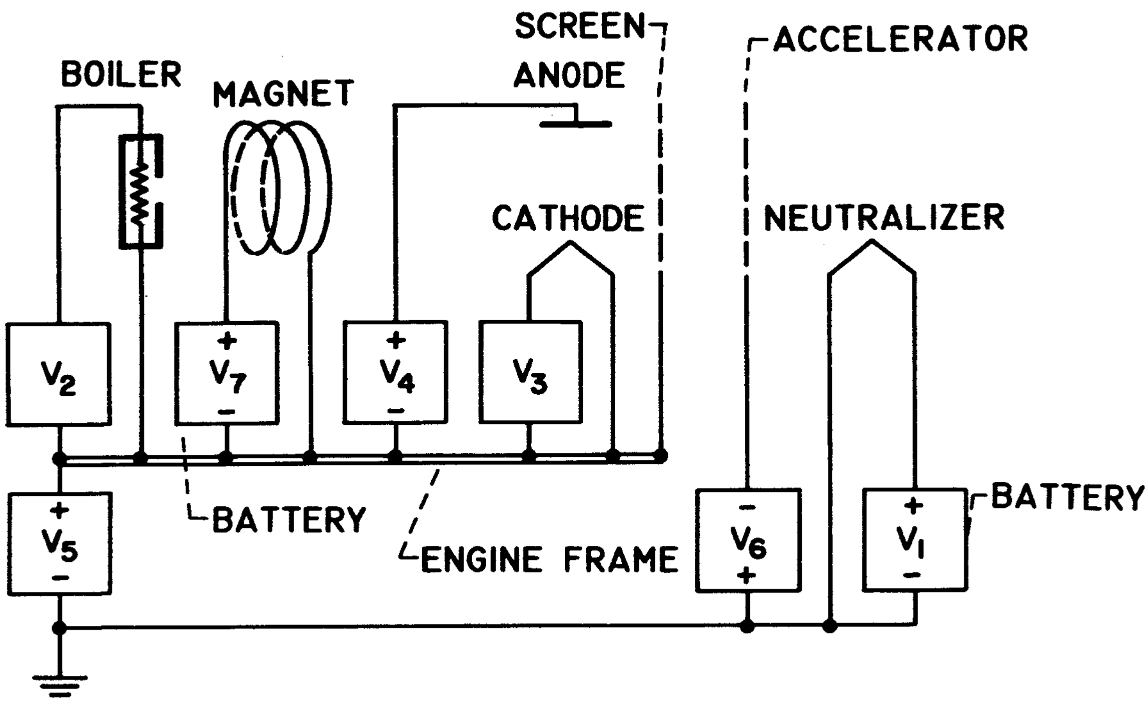

Fig. 4. - Schematic diagram of Sert I Lewis ion thrustor power system.

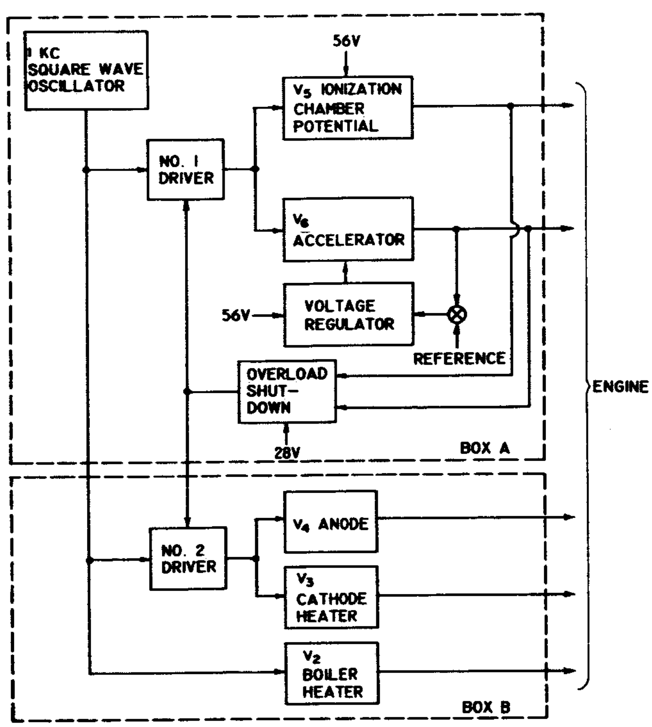

Fig. 5a. - Schematic diagram of Sert I Lewis ion thrustor power system.

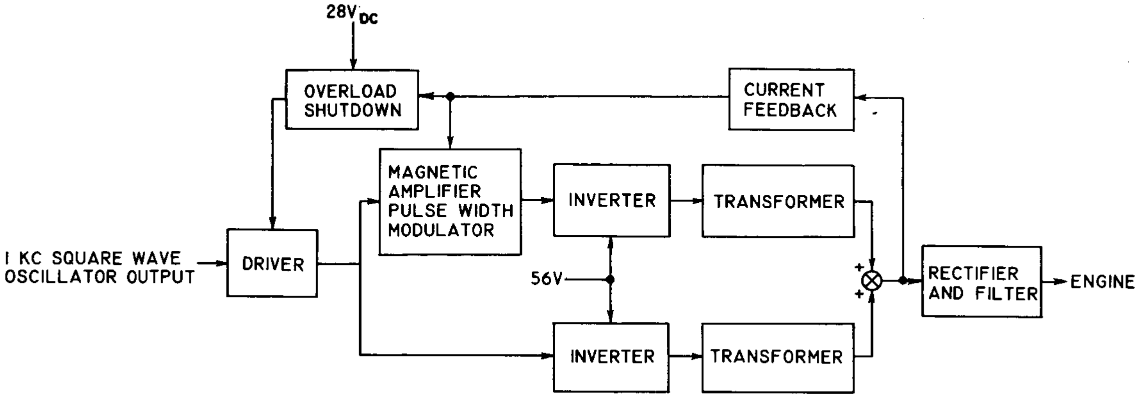

Fig. 5b. - Concluded. Typical high-voltage power supply for Lewis ion thrustor.

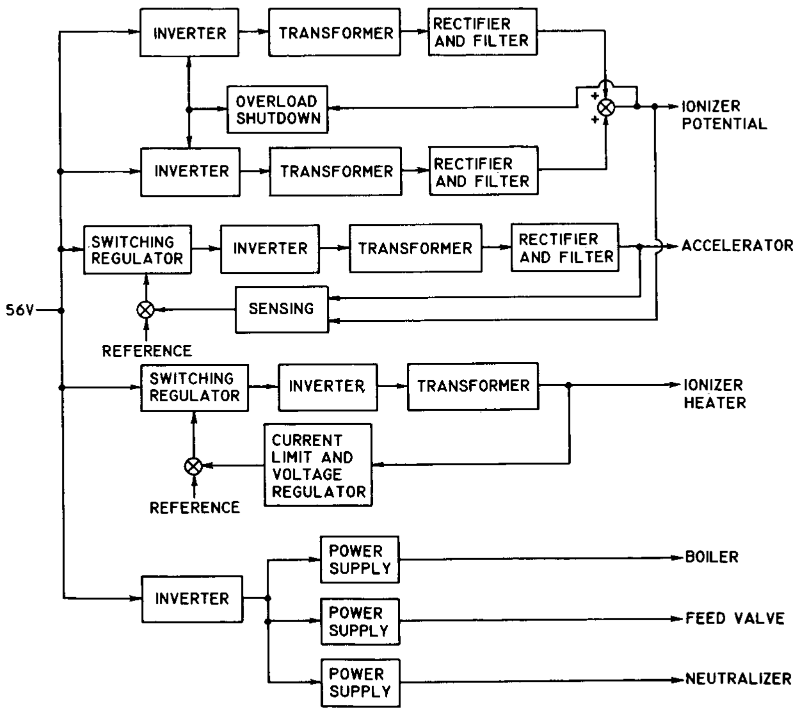

Fig. 6. - Schematic diagram of Hughes 3kw ion thrustor power system.

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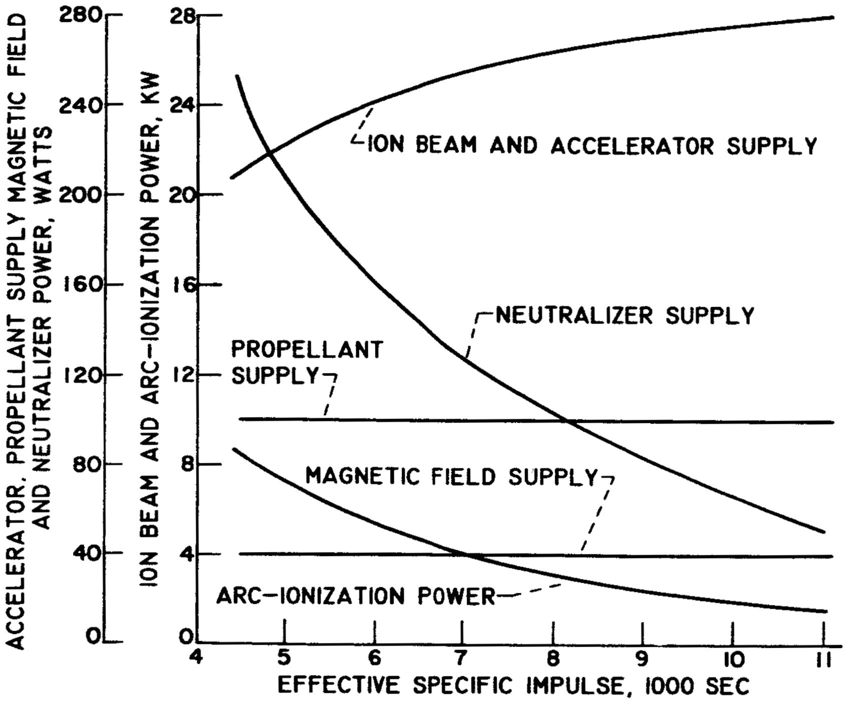

Fig. 7. - Power distribution of 30-kw-module cesium electron-bombardment ion engine system.

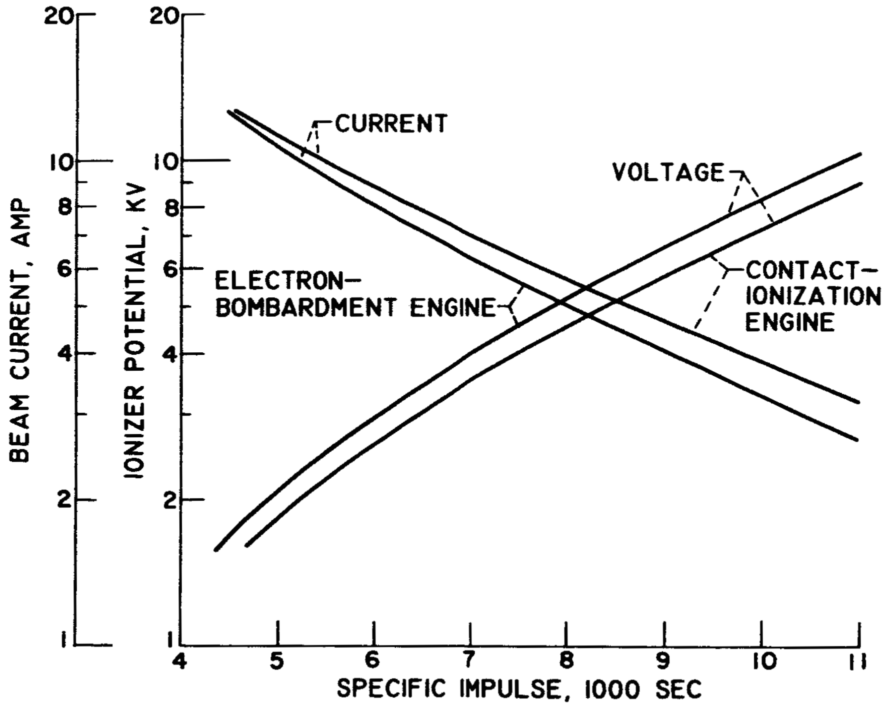

Fig. 8. - Current and voltage characteristics for 30 kw thrustors.

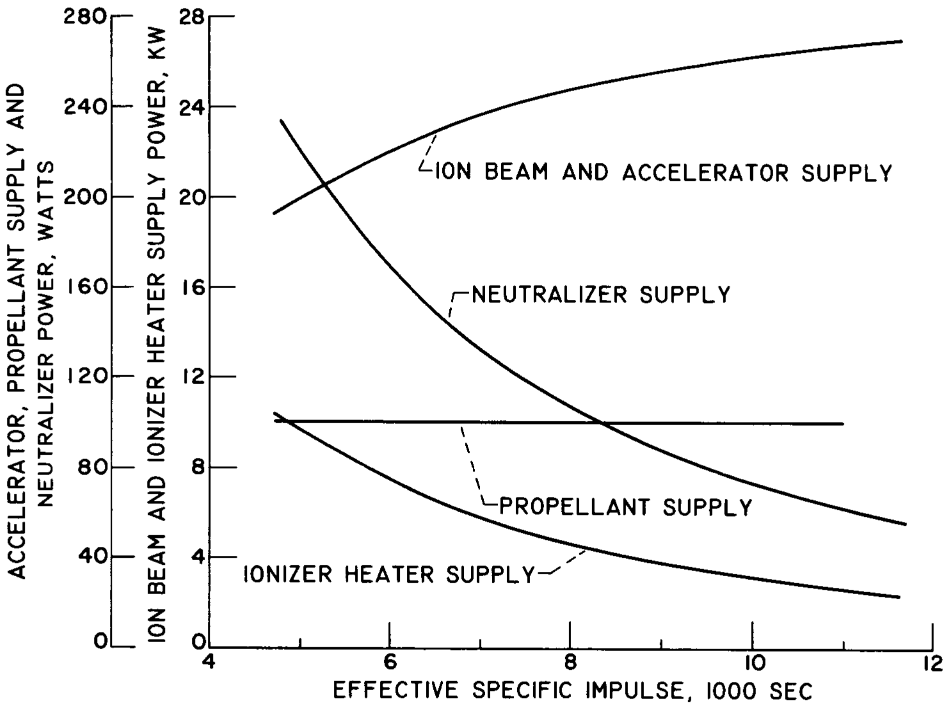

Fig. 9. - Power distribution of 30-kw-module cesium contact-ionization ion engine system.